MOBILE BIOCHEMICAL PRESENCE SURVEY INSTRUMENT

Final Report

JPL Task 1009

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A. OBJECTIVES

The search for evidence of water, ancient and extant, as well as for any hint of biological activity on Mars, represents one of the greatest pursuits and challenges of our present epoch as mankind begins the hunt for non-terrestrial life processes in the universe. On Earth, in the deep Antarctic lakes at Vostok and South Pole; at Europa and Callisto; and on cometary/asteroidal bodies; the paramount need is to rapidly detect and identify the presence of both organic material and lifelike replication processes. A powerful search strategy is required and UV fluorescence techniques are a proven approach to detecting a large, significant segment of these molecular and cellular structures. Many of the instruments presently under development for bio-signature detection require sampling from very small regions (typically less than a few mm square) and many utilize reagent consumables. Most of those measurements require some type of sample preparation and have cycle times of many minutes to hours. Even those that are surface or coring-residue analyzers have long measurement times for very small sampling areas. The life-detection strategy that was developed within the JPL Center for Life Detection suggested that the first step should be a rapid, large-area-coverage detection scheme for potentially interesting targets that would be further examined by higher-definition, more quantitative instruments once a worthwhile site was located. (Find the haystack before beginning to look for the needle.)

This two-year research-and-development effort focused on the maturing and utilization of the UV-fluorescence approach for biochemical detection by advancing several specific component technologies and demonstrating their worthiness in laboratory and field-survey conditions. The specific tasks undertaken were:

1. Conceive and prototype a quite small, fast-response UV-Visible-light fluorescence imager that could rapidly determine the presence of organic material in rock or dust (for Mars) and the presence of spores or bacteria in a water-ice matrix (for Lake Vostok, Europa-like bodies, and possibly Mars polar-cap regions).

2. Advance the state of development of the 224 nm hollow cathode laser, and demonstrate its application as a unique light source for excitation of biochemical materials. Work towards a small laser unit (30% size reduction from 35 cm length to around 25 cm), retaining adequate lifetime and source flux levels. Incorporate the laser into at least one field application as a demonstration test.
3. Advance the state of the Hybrid Imaging Technology detector to enable a very low-power (<150 mW vs. 2+W current CCD requirements), addressing-specific imager that would satisfy both spectroscopic and imaging-detector requirements that would arise as a consequence of the instrument concept and development effort.
4. Test one or more instrument prototypes in field studies that attempted to address specific scientific questions and would adequately demonstrate the utility of the UV fluorescence approaches proposed for future flight missions.

B. PROGRESS AND RESULTS

1. Science Data

Within this specific DRDF study, no real science data were generated. The task was focused on the development of instrument concepts, advancing several component technologies, and on preparation of instrumentation packages that could be tested in the field under the auspices of other programs for validity of concepts and operational usefulness. Within the sponsorship of those other programs (ASTEP and ASTID), science data have been and are being generated. That work will be published under those programs.

2. Other Results

UV Fluorescence Studies

Delays in acquiring a HIT (Hybrid Imaging Technology) array detector led us to use a series of bandpass-filtered photomultipliers (PMTs) to achieve the detection capability we required for instrument development and testing. An example of the first of these instruments is shown in figure 1. This is the first assembly of the 224-nm UV hollow cathode laser with a four-PMT detection system. The outer skin of the instrument has been removed to show the interior construction with the four PMT detectors and their attached bandpass filters, the laser tube and its gas reservoir, and the interface and control electronics. All this fits within the 4.0-inch-diameter outer skin. The laser power supply is the lavender-colored box that also controls the laser firing repetition rate and discharge voltage. The laptop provides command and control, as well as a data-received presentation. The instrument was calibrated in the laboratory against known concentrations of benzene, toluene and xylenes to determine the system sensitivity and reproducibility. It could determine the presence of these chemicals to < 100 ppb in nano-pure water. The calibration was performed in a baked (500°C), clean, pyrex closed-loop pump system, utilizing magnetic stirring. The pump is shown in figure 2a, and with the instrument looking into a dye in the water for testing complete laser absorption (figure 2b).

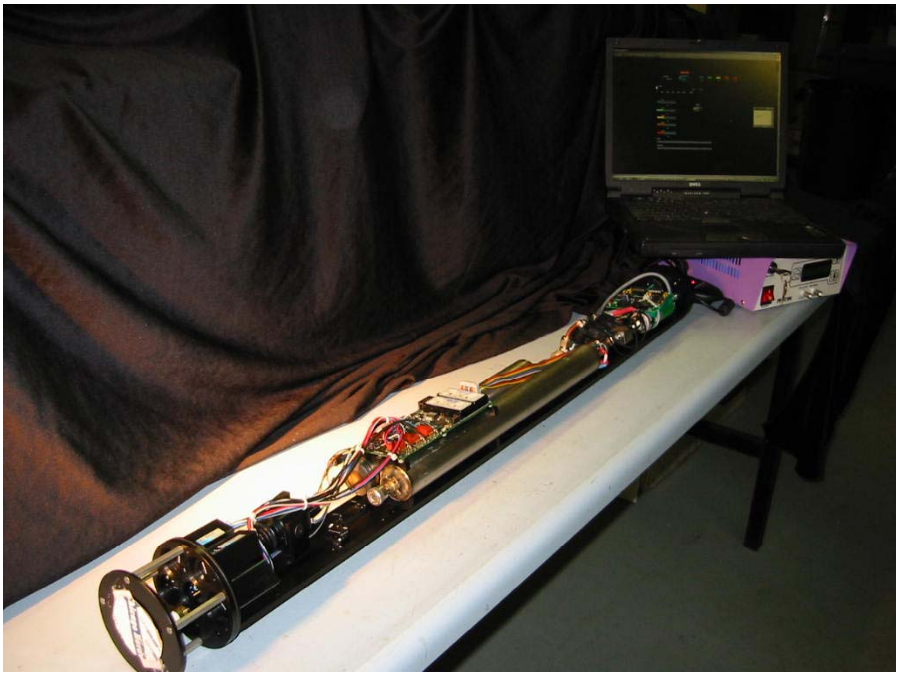

Figure 1. The first 224-nm laser 4-channel fluorimeter. Instrument is 10 cm in diameter and 110 cm long, weighing about 14 kg. It was designed to fit inside pollution test wells at Edwards Air Force Base.

Fig 2a. The water circulation pump for calibration of instrument fluorescence response.
Fig 2b. The instrument over the calibration test fluid, with a red dye added for visibility.

The instrument was successfully deployed twice at Edwards Air Force Base, and demonstrated that it could detect sub-ppm concentrations of BTEX materials in the groundwater wells. The fluorescence signatures were strong and measurements were accomplished in 30 to 120 seconds.

The second instrument concept developed was the multi-channel deep-UV fluorimeter McDUF2 that improved upon the initial instrument by efforts to eliminate the external high-voltage power supply and to provide a more quantitative knowledge of the intensity of the UV-emission light pulses. Within the envelope of size and power limitations imposed by a realistic planetary in situ flight mission, it was not possible to shrink the laser power supply to the desired volume and power consumption, while retaining pulse rates of 100 to 200 Hz and a discharge time duration of ~100 µs. When pulse rate was reduced to 1-5 Hz, the power supply and its controller functions were reduced to the size of a small printed-circuit card, and could be fit within a 10-cm instrument shell. The average power consumption also dropped to around 1 W. This new configuration enabled a self-contained instrument with no external boxes. The new driver boards were designed by Photon Systems, Inc. and tested by them to prove their capability. The intent was to test the new McDUF2 instrument in the same pollution wells as before at Edwards Air Force Base, CA (EAFB), but that program ended before we could complete a new instrument build. Designs were finished to enable a 9-cm-diameter probe of <1m length, but the fabrication could not be completed without a new program to support that development.

An opportunity arose to take the work on McDUF2 and finish a new instrument when James Cameron invited JPL to join his 3-D IMAX film team in exploring a set of hydrothermal vents in the East Pacific Rise off the west coast of Mexico and Guatemala. That configuration, very much like McDUF2 but "hardened" to endure multiple cycles in deep ocean water to 4500 m, was built and tested. After solving a few problems with the optical quartz crystal windows, which suffered crack formation by drum-head deformation of the window-mount flange, the instrument, McDUVE (Multi-channel Deep UV Vent Experiment), successfully passed all imposed tests and dove to 2600, 2500 and 2000 m when attached to the Russian MIR 1 submersible.

Figure 3 shows the block diagram for the McDUVE instrument. The laser emission is monitored for intensity and stability on every pulse, and an internal channel monitors the electronic drift (if any) on the fluorimeter board that contains the sensitive integrating capacitors that provide charge storage from the PMT signal chain. The data system resided on a laptop inside the submersible, with command, control and data viewing under the immediate control of the scientist using the instrument. A wide range of measurements were performed on those three dives to three different sites; the instrument performed extremely well and the data acquired are now being analyzed for publication.

Figure 4 shows McDUVE attached to the port manipulator arm of MIR 1. This attachment method enabled the instrument to be pointed to a variety of targets and geometries in front of the MIR, where the scientist and the MIR pilot could observe the measurement configuration and placement. The PMTs in McDUVE are extremely sensitive. The best measurements at the hydrothermal vent chimneys, of the bio-mats that formed around the sea floor near the chimney and the biomaterial in the water column, were all performed with all lights out on the MIR and the viewing windows covered to prevent small amounts of scattered light from interfering with those measurements.

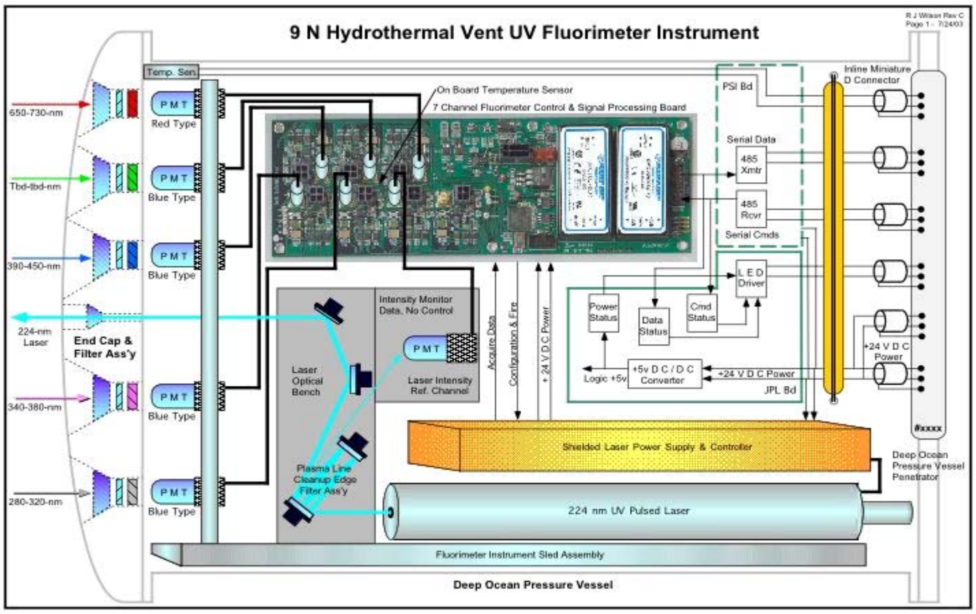

Figure 3. The block diagram of the McDUVE instrument. The entire instrument was mounted on a "sled" that fit within the 11.5-cm internal diameter of the 6Al4V titanium housing. The pressure shell was 12.5 cm in outer diameter and 1 m long. It weighed about 35 kg full assembled.

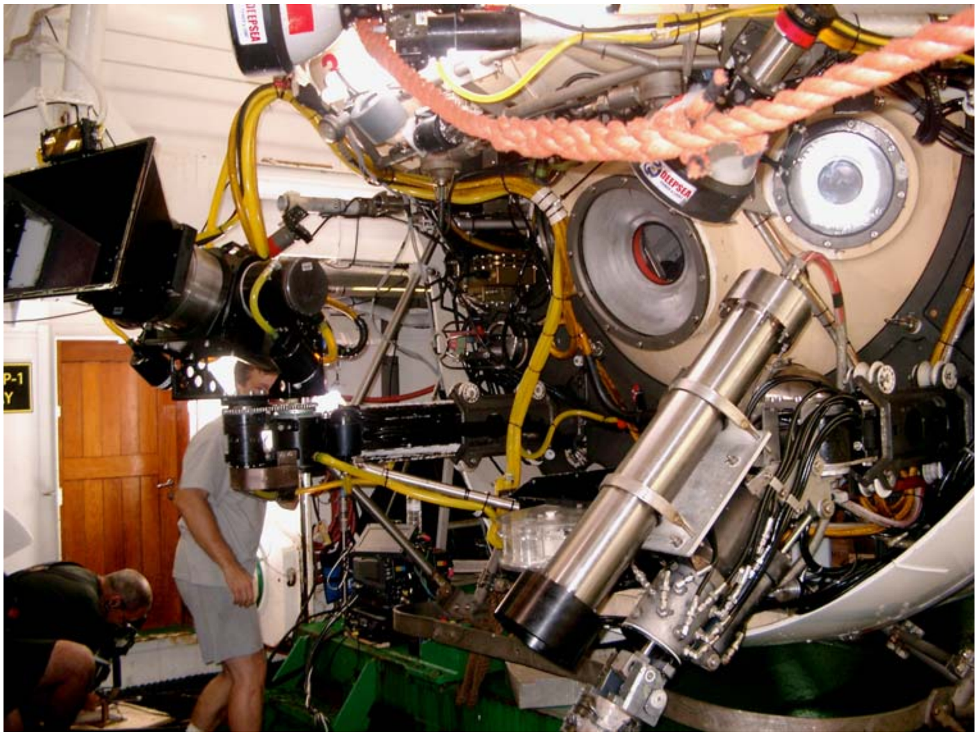

Figure 4. The front of MIR 1 with the McDUVE instrument on the right side of the picture (MIR port) and the Cameron 3-D IMAX camera on the left side (MIR starboard). The scientist is behind the viewport nearest McDUVE.

While the deep-water McDUVE was in development, the dry-land version was being designed and built as part of an ASTEP grant to Dr. Pan Conrad. This instrument used the same principles developed in this DRDF, but the application to examine rocks and surfaces led to a convergent beam design where the laser illumination spot was focused to be 5 to 8 cm below the instrument and each of the PMTs looked inwardly at this beam location. This geometry provided enhanced sensitivity for close-by objects. The advances in control and high-voltage electronics enabled the instrument to shrink significantly in overall size; it is now slightly bigger than a shoebox and weighs less than 10 kg. Figure 5 shows this version of McDUVE during its first field test on the salt beds in Death Valley, CA.

Figure 5. McDUVE examining green bacteria in the salt beds at Bad Water in Death Valley, CA.

The work of improving McDUVE for dry-land field work will continue under the auspices of the ASTEP program.

The HIT development will continue under a two-year MIDP grant to A. Lane. It is anticipated that a new silicon foundry run will be finished in mid-spring 2004, and that HIT detectors will be available for characterization during the summer of 2004. When a full-up HIT camera is assembled and characterized, that imaging sensor will be tested for performance capability as a fluorescence imager and as a spectrograph detector for future fluorescence instruments.

C. SIGNIFICANCE OF RESULTS

This task developed two of the critical components required to assemble several versions of UV-fluorescence instruments for the detection of biochemicals and organisms. The team proved that not only was UV fluorescence a powerful tool with great low-concentration sensitivity, but also that small, low-power, yet very capable instruments could be conceived, prototyped and deployed in field conditions for important science measurements. The concepts developed in this DRDF enabled a “solicited” proposal (MIOPA) to be presented to the Mars Exploration Rover project for an inexpensive add-on to the deployment-arm-mounted microscopic imager. Unfortunately, although NASA HQ was very interested and there was sufficient time to build and test the add-on hardware, NASA decided not to proceed with the development. The MIOPA proposal provided the basis for future work and furthered the concepts for utilization of UV fluorescence as a biochemical survey instrument. The work is directly applicable to the 2009 Mars Science Laboratory rover mission requirements, and an improved concept based upon this work will be submitted in response to the soon-to-be-released Announcement of Opportunity for science investigations.

The results indicate that a low-power Hollow Cathode Laser operating at either 224 or 248 nm can be fabricated and operated in a long-duration pulsed mode (~100 µs on time) at a few-Hz rate with a power consumption of < 1 watt. Laser tube size can also be reduced in length from about 35 cm to around 25 cm and still maintain a useful lifetime of greater than several million pulses (more than enough for a 2-year active-duration in situ mission). The laser wavelengths chosen in the UV enable strong excitation coupling and bright fluorescence emissions for the classes of polycyclic aromatics that are found in SNC meteorites believed to have a Martian origin. These types of chemical compounds are among the most likely degradation products of organic biomaterials (and perhaps among the most stable) and should be present on Mars if there were development of biosynthesis during parts of Mars' evolutionary history. The wavelengths of fluorescence observed with excitation at 224 nm permit detection and ring-complexity separation for one-, two-, three-, four- and five-member aromatic rings. Other heterocyclic ring structures incorporating either nitrogen or oxygen also have fluorescence signatures when activated by 224-nm light; but they have discernibly different fluorescent spectral patterns.

The HIT detector development did not proceed as well as anticipated or planned. A number of problems arose with the vendors providing the CCD basic silicon structures, and one silicon foundry that performed very well in earlier, initial test runs prior to this DRDF was not able to continue supporting our small, fractional-lot fabrication requests. The designs for the on-chip amplifiers and signal-chain-driver electronics were completed and await fabrication runs. Because of the fabrication issues at the foundries and the per-lot fabrication costs of $200-to-300K, we did not have sufficient funding for our own run, nor were we able to find a shared-cost activity with some other fabrication customer during the time this proposal was active. (The HIT studies performed during this DRDF and during a FY'03 R&TD task enabled a NASA MIDP proposal to be funded; that proposal has found a shared-fabrication-run sponsor and we expect to see our first special run chips in the late-May 2004 timeframe. The HIT development of a prototype flight detector will continue under that MIDP award.)

The UV-fluorescence instrument concepts matured into two field instruments performing in vastly different domains: water & ice, and surface-material investigations.

One instrument was developed for examination of biochemical signatures in deep-water and deep-ice environments. It was deployed in its first configuration in support of a groundwater pollution study at EAFB. The instrument demonstrated the ability to detect

BTEX pollutants in water (benzene, toluene, ethyl benzene and xylene; all single-phenyl-ring chemicals) over the range from 400+ ppm down to ~100 ppb, with a measurement time of a few seconds. The measurements were performed in situ in the EAFB wells. That instrument was not optimized for that specific task; simple modification should drive the detection limit down to around 10 ppb in water. From what was learned during this effort, a second instrument (the James Cameron instrument, McDUVE) was developed for deployment to deep hydrothermal vents to study possible emission of biomaterials directly from the vents. This task was funded by a different program, still under the auspices of the Chief Scientist, but used the results of the development efforts funded by this specific task. The McDUVE instrument successfully operated at 2600-m depth (~260 bars) and appears to have detected biomaterial emanating from the throats of several vents along the East Pacific Rise and in the Guaymas Basin at 2000-m depth. A simple modification of McDUVE will enable it to explore the bottoms of deep, hot-water drilled boreholes in glaciers and ice sheets. A deployment in Antarctica is under study.

The second instrument developed from the concepts and approaches of this DRDF task utilizes a focused-zone interrogation approach in which the deep-UV laser and the sensing PMTs all view a common spot very close to the instrument. It has been fabricated under a different NASA task, but once again, almost all the principles, concepts and component testing were derived from this DRDF. This second instrument, now being deployed in the field for astrobiology studies in geological settings, has great near-field sensitivity – into the femto- and atto-molar-concentration range for certain classes of biochemical molecules, and into the range of tens of biological cells. The instrumental concept will be developed to propose as an instrument for the Mars ’09 Science Laboratory.

D. FINANCIAL STATUS

The total funding for this task was $244,400, all of which has been expended.

E. PERSONNEL

In addition to the PI and the listed Co-Investigators, Rohit Bhartia contributed significantly to the success of the fluorescence-instrument development. He assisted in a number of the calibration efforts, developed almost all of the software and processing code, and was an active participant in a number of the field tests.

Significant hardware-design support came from Photon Systems, Inc., which was part of the EAFB and ASTEP tasks.

F. PUBLICATIONS

None.